

A search for charged massive long-lived particles at D0

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We report on a search for charged massive long-lived particles (CMLLPs), based on 5.2 fb^{-1} of data collected with the D0 detector at the Fermilab Tevatron $p\bar{p}$ collider. CMLLPs are predicted in many theories of physics beyond the standard model. We look for events in which one or more particles are reconstructed as muons but have speed and ionization energy loss dE/dx inconsistent with muons produced in beam collisions. We present 95% C.L. upper limits on the production cross section for long-lived scalar taus, for long-lived charginos in two SUSY scenarios, and for long-lived scalar top quarks. We also present exclusion mass ranges for the chargino and scalar top quark models.

1. Introduction

We report on a new search for massive particles, which are electrically charged and have a lifetime long enough to escape the D0 detector before decaying. Charged massive long-lived particles (CMLLPs) are not present in the standard model (SM) nor are their distinguishing characteristics (slow speed, high dE/dx) relevant for most physics studies. Although the distinctive signature in itself provides sufficient motivation for a search, some recent extensions to the SM suggest that CMLLPs exist and are not yet excluded by cosmological limits [1, 2]. Indeed, our present model of big bang nucleosynthesis (BBN) has difficulties in explaining the observed lithium production. The existence of a CMLLP that decays during or after the time of BBN could resolve this disagreement [3].

We derive cross section limits for CMLLPs and compare them to theories of physics beyond the SM. Supersymmetric (SUSY) models can predict either the lightest chargino or the lightest scalar tau lepton (stau) to be a CMLLP. We study a gauge-mediated supersymmetry breaking (GMSB) model in which the next-to-lightest supersymmetric particle (NLSP) is a long-lived stau lepton [4–6]. Other explored models predict a light chargino whose lifetime can be long if its mass differs from the mass of the lightest neutralino by less than about 150 MeV [7, 8]. This can occur in models with anomaly-mediated supersymmetry breaking (AMSB) or in models that do not have gaugino mass unification. There are two general cases, where the chargino is mostly a higgsino and where the chargino is mostly a gaugino, which we treat separately.

There are some SUSY models that predict a scalar top quark (stop) NLSP and a gravitino LSP. These stop quarks hadronize into both charged and neutral mesons and baryons that live long enough to be CMLLP candidates [9]. Further, hidden valley models predict GMSB-like scenarios where the stop quark acts like the LSP and does not decay, but hadronizes into charged and neutral hadrons that escape the detector [10, 11]. In general, any SUSY scenario where the stop quark is the lightest colored particle (which will happen in models without mass unification and heavy gluinos) can have a stop CMLLP. Any colored CMLLP will have additional complications of hadronization and charge exchange during nuclear interactions, which we discuss below.

This search utilizes data collected between 2006 and 2010 with the D0 detector [12] at Fermilab's 1.96 TeV $p\bar{p}$ Tevatron Collider, and is based on 5.2 fb^{-1} of integrated luminosity. We reported earlier [13] on a similar 1.1 fb^{-1} study, searching for events with a pair of slow-moving massive charged particles. In addition to using the larger data sample, the present search looks for one or more CMLLPs, characterized by high dE/dx as well as by slow speed. Further, we explore predictions for long-lived stop quarks as well as for stau leptons and charginos, which were considered earlier. Other searches for long-lived particles include those from the CDF Collaboration [14, 15], the CERN e^+e^- Collider LEP [16], and the CERN pp collider LHC [17, 18].

2. The D0 Detector

The D0 detector [12] includes an inner tracker with two components: an innermost silicon microstrip tracker (SMT) and a scintillating fiber detector. We find the dE/dx of a particle from the energy losses associated with its track in the SMT. The tracker is embedded within a 1.9 T superconducting solenoidal magnet. Outside the solenoid is a uranium/liquid-argon calorimeter surrounded by a muon spectrometer, consisting of drift tube planes on either side of a 1.8 T iron toroid. There are three layers of muon detector planes: the A-layer, located between the calorimeter and the toroid, and the B- and C- layers, outside the toroid. Each layer includes planes of scintillation counters which serve to veto cosmic rays. Thus the muon system provides multiple time measurements from which the speed of a particle may be calculated.

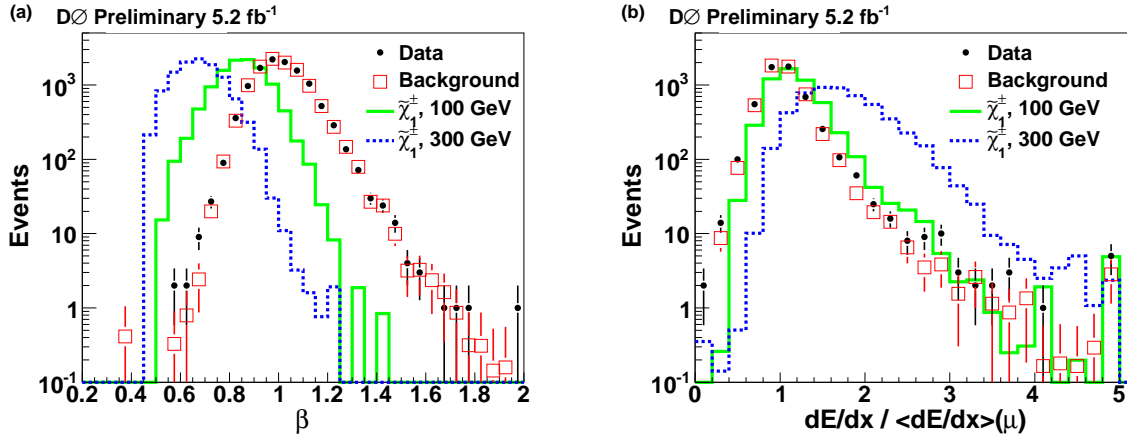


Figure 1: Distributions of (a) speed (β) and (b) dE/dx for data, background, and signal (gaugino-like charginos with a mass of 100 and 300 GeV) that pass the selection criteria. The histograms have been normalized to have the same numbers of events. We have adjusted the scale of the dE/dx measurements so that the dE/dx of muons from $Z \rightarrow \mu\mu$ events peak at 1. All entries exceeding the range of the histogram are added to the last bin.

3. Important Variables

Because we distinguish CMLLPs solely by their speed (β) and dE/dx , we must measure these values in each event as accurately as possible. Muons from $Z \rightarrow \mu\mu$ events studied throughout the data sample allow us to calibrate the time measurement to better than 1 ns, with resolutions between 2-4 ns, and to maintain the mean dE/dx constant to within 2% over the data-taking period. From a specific muon scintillation counter we calculate a particle's speed from the time recorded and the counter's distance from the production point, and we compute an overall speed from the weighted average of these individual speeds, using measured resolutions. The ionization loss data from the typically 8-10 individual hits in the SMT are combined using an algorithm that omits the largest deposit to reduce the effect of the Landau tail and corrects for track crossing angle. We calibrate the dE/dx measurements so that the dE/dx of muons from $Z \rightarrow \mu\mu$ events peak at 1. Figure 1 shows the distributions in β and dE/dx for data, background, and signal (defined in Section 5).

4. Event Selection

Selection of a candidate CMLLP event begins immediately at the time of the interaction. Because of the high collision rate, we employ a three-level trigger system to reduce the event rate to the 200 Hz that can be recorded. The trigger system bases its decisions on characteristics of the event, which for the CMLLP candidates is the presence of a muon with a high momentum transverse to the beam direction (p_T). In order to reduce triggers on cosmic rays, there is a time window at the initial trigger level. This trigger gate reduces the trigger efficiency by 10% for CMLLPs with a mass of 300 GeV (as they will be slow and some will be out-of-time) and contributes significantly to our overall acceptance. We avoid a tighter timing gate usually imposed at the second level of the muon trigger by accepting an alternative requirement that the muon have a matching track in the SMT.

In the standard event reconstruction CMLLPs would appear as muons. Thus, we select events with at least one well identified high p_T muon. For a useful β measurement, the event must have scintillator hits in the A-layer and either the B- or C-layer, and for a valid dE/dx measurement, we require at least three hits in the SMT. For an optimal tracking and momentum measurement we require the muon to be central, i.e., with a pseudorapidity¹ $|\eta| < 1.6$. To reject muons from meson decays we impose the isolation requirement that the sum of the p_T be less than 2.5 GeV for all other tracks in a cone of radius $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.5$. We also require that the total transverse calorimeter energy in an annulus of radius $0.1 < R < 0.4$ about the muon

¹ The D0 coordinate system is cylindrical with the z -axis along the proton beam direction, and the polar and azimuthal angles are denoted by θ and ϕ , respectively. The pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$.

direction be less than 2.5 GeV. A requirement that the coordinate along the beam direction of the distance of closest approach of the muon track to the beam axis be < 40 cm ensures that the particle passes through the SMT.

We impose criteria to eliminate cosmic rays. To select muons traveling outwards from the apparent interaction point, we require that its C-layer time be significantly greater than its A-layer time. We require also that the muon's distance-of-closest-approach to the beam line be less than 0.02 cm. These criteria are also applied to a second muon in the event, if a second muon is present. In addition, for events with two muons we require that the absolute value of the difference between each muon's A-layer times be less than 10 ns. To reject cosmics that appear as two back-to-back muons, we require for their pseudo-acolinearity $\Delta\alpha = |\Delta\theta + \Delta\phi - 2\pi| > 0.05$.

Events with a muon from a W boson decay, with mismeasurements providing inaccurate values of the muon's β and dE/dx , constitute a potentially large background. To study selection criteria for CMLLPs, we calculate the transverse mass² M_T , and select data with $M_T < 200$ GeV to model the data in the absence of signal³. We choose selection criteria that minimize the number of events surviving from this background sample compared to events from simulations of CMLLP signal. We require that events contain at least one muon with $p_T > 60$ GeV. From a separate sample of muons from $Z \rightarrow \mu\mu$ decays, we see that the association of a spurious scintillator hit at times gives an anomalously slow β value. We use an algorithm that discards such hits through minimizing the $\chi^2/d.o.f.$ for the β calculated from the different scintillator layers. By comparing the effect on the background sample with the effect on simulated signal, we choose to eliminate events unless the minimized speed $\chi^2/d.o.f. < 2$. Finally, we compare the track direction of the muon measured in the muon system with that measured in the central tracker, and eliminate several events with clearly mismatched tracks.

5. Data and Monte Carlo Samples

To simulate potential signal events, we generate CMLLP candidates using PYTHIA [19]. Samples are generated with PYTHIA for the long-lived stau lepton and chargino models, and the long-lived stop quarks are hadronized using specialized routines interfaced with PYTHIA⁴. Because the signature of the CMLLP cascade decays is model dependent and difficult to simulate accurately, we generate direct pair-production of the CMLLPs, without including cascade decays. We use the full D0 detector GEANT [20] simulation, which includes overlaid multiple $p\bar{p}$ interactions, to determine the detector response for these samples. The results are applicable to models with pair-produced CMLLPs with similar kinematics.

The stop quarks are distinct since they appear in charged or uncharged stop hadrons, which may flip their charge as they pass through the detector. In the simulation approximately 60% of stop hadrons are charged following initial hadronization [21, 22], i.e., 84% of the events will have at least one charged stop hadron. Further, stop hadrons may flip their charge through nuclear interactions as they pass through material. We assume that stop hadrons have a probability of 2/3 of being charged after multiple interactions and that anti-stop hadrons have a probability of 1/2 of being charged [21, 22]. For this analysis we require the stop hadron to be charged before and after passing through the calorimeter, i.e., to be detected both in the tracker and in the A-layer, and to be charged after the toroid, i.e., to be detected in the B- or C-layers. The probability for at least one of the stop hadrons to be detected is then 38%, or 84% if charge flipping does not occur. We include these numbers as normalization factors in the confidence level analysis discussed below.

Our final selection criteria is that the candidate's speed $\beta < 1$. Thus, we describe the background by the $\beta < 1$ data events with $M_T < 200$ GeV, and search for CMLLP candidates in $\beta < 1$ data with $M_T > 200$ GeV. We normalize the background and data samples in the $\beta > 1$ signal-free region. Because the uncertainties in the speed measurements depend on the particle's η , due to detector geometry, and the distributions in η of the muons in the $M_T < 200$ GeV sample differs from those in the $M_T > 200$ GeV sample, we use the signal-free region to derive a reweighting of the background sample that matches its η distribution to that of the data.

²The transverse mass is defined by $M_T = \sqrt{(E_T + \cancel{E}_T)^2 - (p_x + \cancel{p}_x)^2 - (p_y + \cancel{p}_y)^2}$ where E_T is the total energy transverse to the axis of the colliding beams and \cancel{E}_T is the total unbalanced or missing transverse energy.

³The requirement $M_T < 200$ GeV is customarily used to select W events.

⁴The code for hadronizing stop quarks is at <http://projects.hepforge.org/pythia6/examples/main78.f>

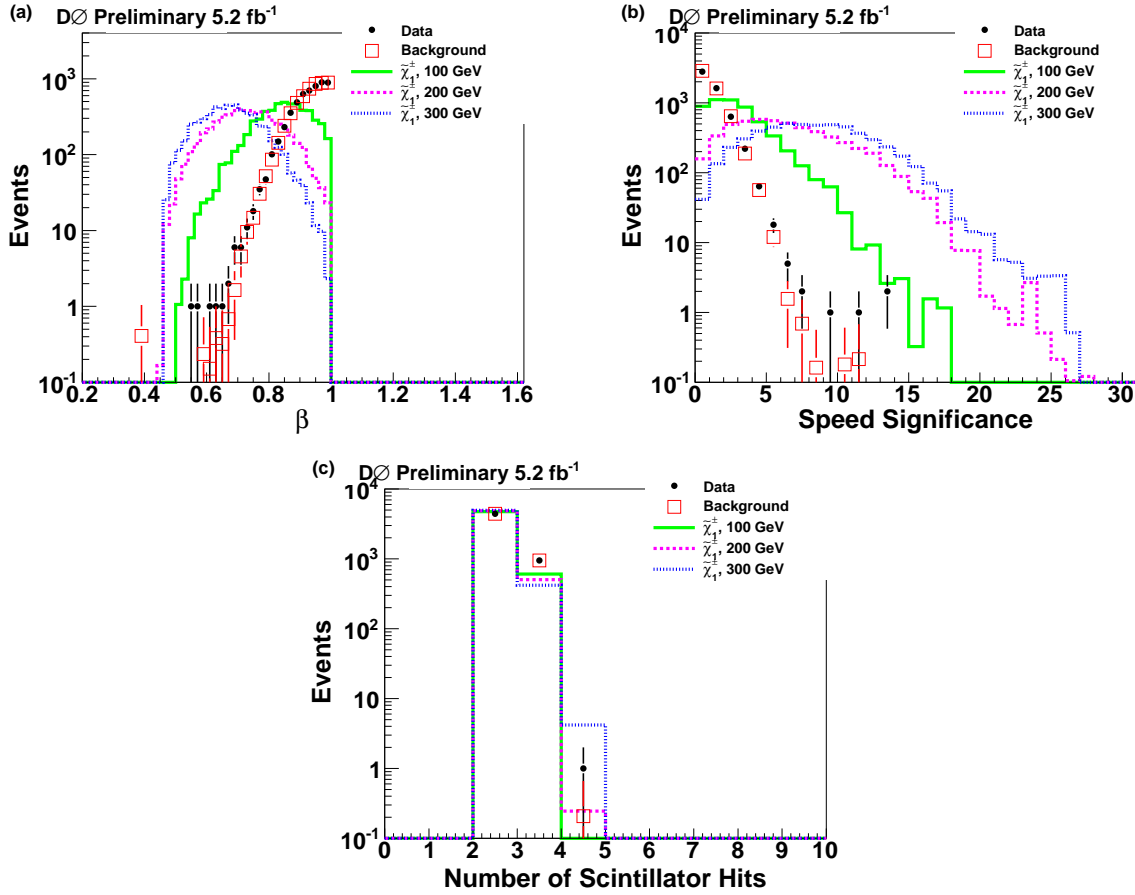


Figure 2: Final distributions related to the speed for signal (100, 200, and 300 GeV gaugino-like charginos), background, and data. The speed distribution (a), speed significance distribution (b), and number of scintillator hits distribution (c). For each plot, the histograms have been normalized to have the same number of events.

6. Final Discriminants

We utilize a boosted decision tree (BDT) [23] to discriminate signal from background. The discriminating variables are the CMLLP candidate's β and dE/dx , as well as several related variables: the speed significance, defined as $(1 - \beta)/\sigma_\beta$, the corresponding number of scintillator hits, the energy loss significance defined as $(dE/dx - 1)/\sigma_{dE/dx}$, and the number of SMT hits. For each mass point in all four signal models we train the BDT with the signal MC and the background, and then apply it to the data samples. Figure 1 shows the distributions in β and in dE/dx for the data and background samples, as well as for a signal (gaugino-like charginos of mass 100 and 300 GeV). Figures 2 and 3 show the discriminating variables that are input to the BDT, for data, background, and signal. Figure 4 shows the correlations between input variables to the BDT, for background and a representative signal. Figure 5 shows the BDT output distributions for three representative signals: 100, 200, and 300 GeV gaugino-like charginos.

7. Results

Systematic uncertainties are studied by applying variations to the data, background and signal samples and determining the deviations in the BDT output distributions. Two systematic uncertainties affect the shape of the BDT distributions, and their effect is taken into account explicitly in the limit calculation: the uncertainty due to the width of the Level 1 trigger gate and the uncertainty of the time simulation in MC. Both of these uncertainties are applied only to signal. By examining the signal-like region of the BDT distributions, we find that the maximum (average) uncertainty is 10% (4%) for the trigger gate width and 38% (7%) for the time

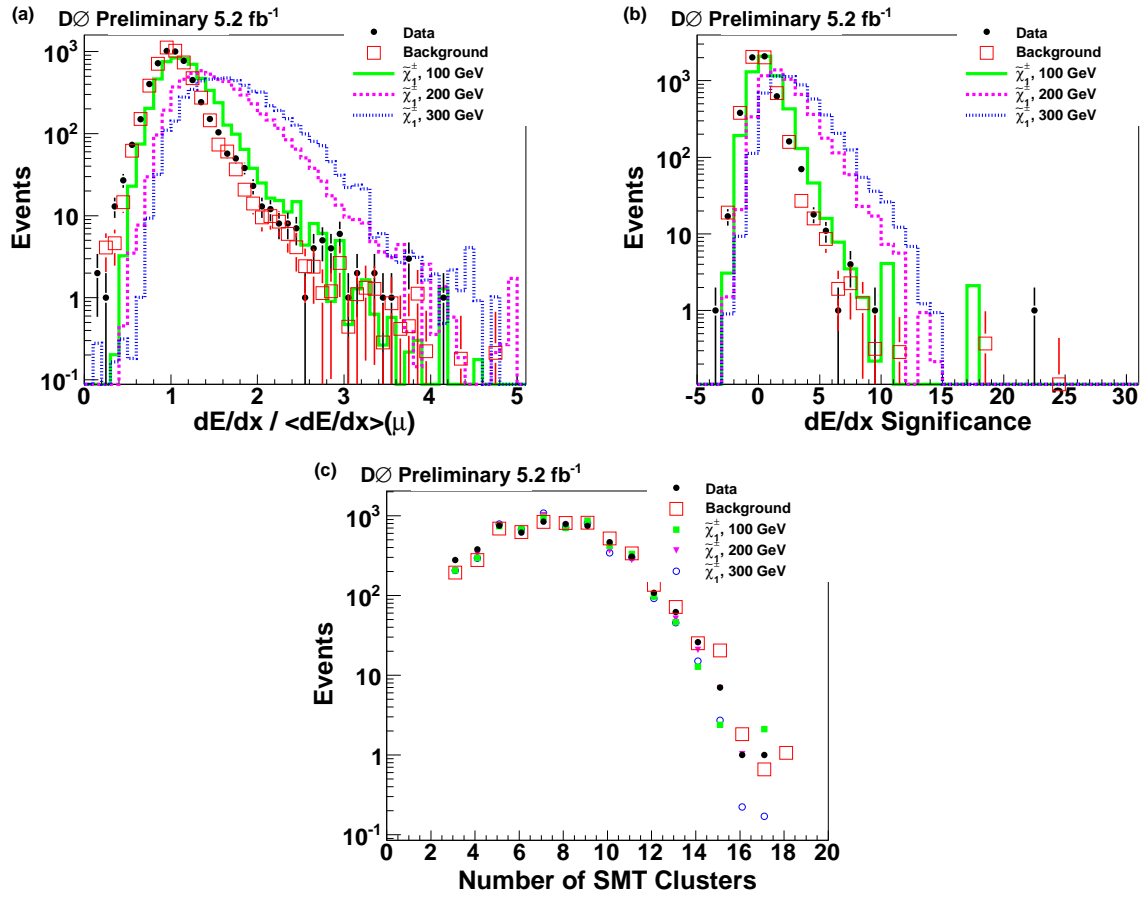


Figure 3: Final distributions related to the dE/dx for signal (100, 200, and 300 GeV gaugino-like charginos), background, and data. The dE/dx distribution (a), dE/dx significance distribution (b), and number of SMT clusters distribution (c). For each plot, the histograms have been normalized to have the same number of events.

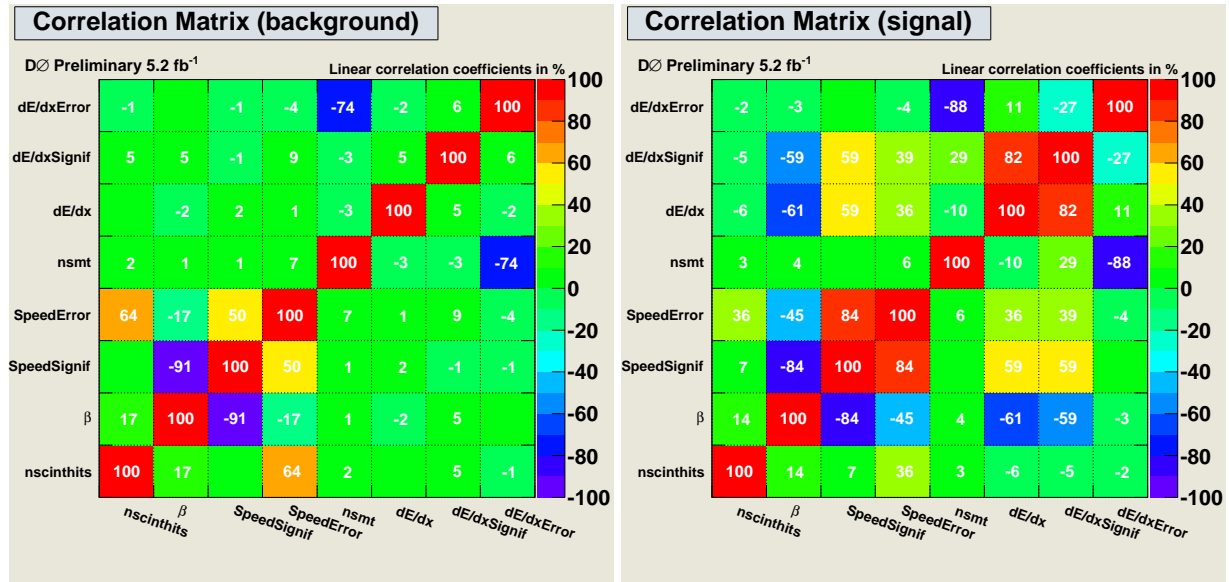


Figure 4: BDT correlation matrices for background and a representative signal (300 GeV staus).

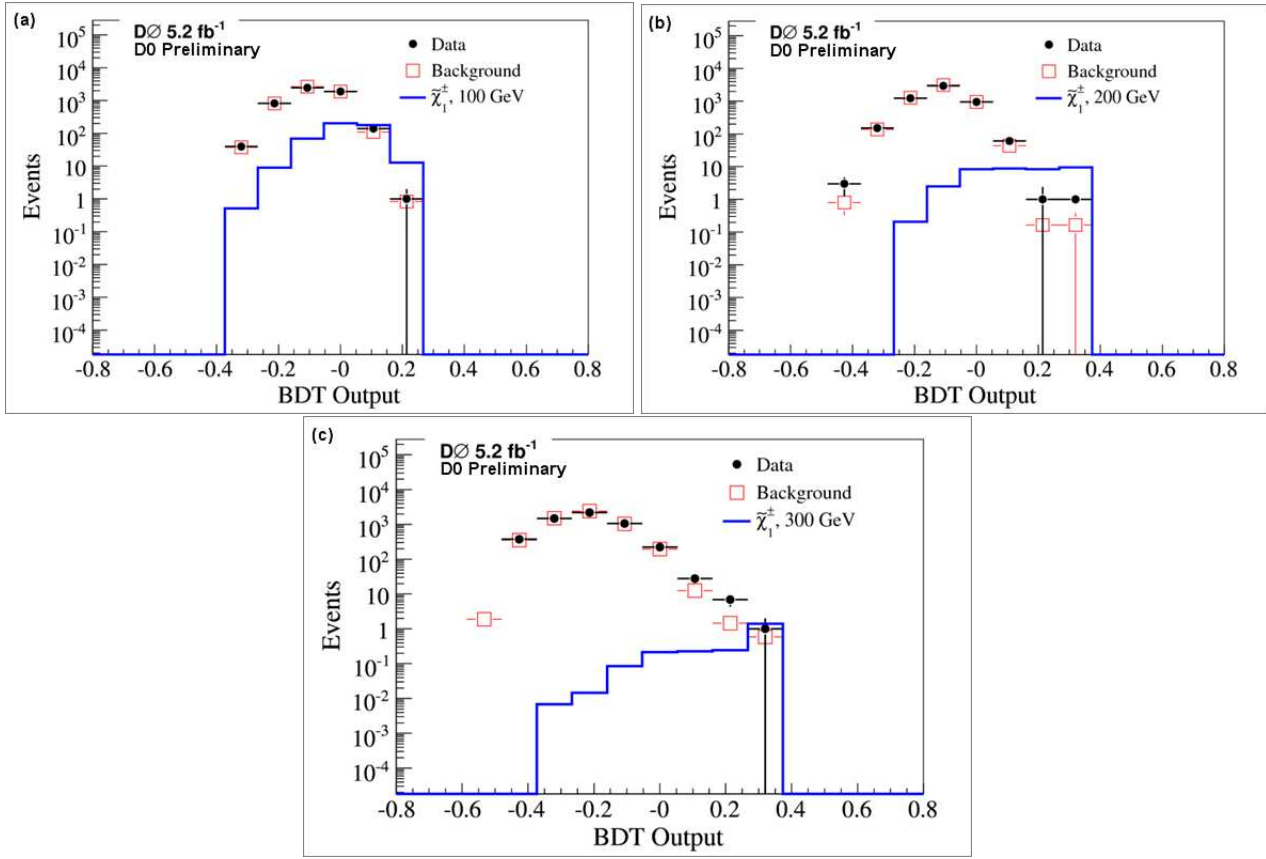


Figure 5: Final BDT distributions for signal, background, and data. For the 100 GeV (a), 200 GeV (b), and 300 GeV (c) gaugino-like chargino cases. For each plot, the signal histograms have been normalized to the expected number of events.

smearing. Other systematic uncertainties affect only the normalization of the BDT output. The systematic uncertainties on the background are due to the dE/dx correction ($< 0.1\%$) and the background normalization (7.5%). The systematic uncertainties on the signal include muon identification (2%) and the integrated luminosity (6.1%) [24]. The systematic uncertainties associated with the muon p_T smearing, the dE/dx smearing and the choice of PDF and factorization scale are all below 1% .

We obtain the 95% C.L. cross section limits from the BDT output distributions, constraining systematic uncertainties to data in background dominated regions [25]. These limits are shown in Tables I, II, III, and IV, together with the NLO theoretical signal cross sections, computed with PROSPINO [26]. The limits vary from 0.04 pb to 0.006 pb for directly pair-produced stau leptons with masses between 100 and 300 GeV. We place similar bounds on the cross sections of other pair-produced CMLLPs. Using the theoretical cross sections, we are able to exclude gaugino-like charginos below 251 GeV and higgsino-like charginos below 230 GeV. For stop quarks, we assume a charge survival probability of 38%, as discussed above, and exclude masses below 265 GeV. If charge flipping does not occur, we would obtain a significantly higher mass limit.

As seen in Tables I, II, III, and IV, the observed limit exceeds the expected limit at various mass points by as much as 2.5 standard deviations, for all signals tested, due to the presence of the same few data events with high BDT discriminant values. This discrepancy reflects the excesses of data compared to background observed in Fig. 1 for the distributions both in beta (around 0.6) and dE/dx (around 2.8). We have compared these events with background events and conclude that the observed excess is consistent with a statistical fluctuation in the number of such events.

Table I: NLO cross-sections and cross-section limits for staus.

Mass [GeV]	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit $\pm 1\sigma$ [pb]
100	0.0121	0.0400	$0.0263^{+0.0109}_{-0.0075}$
150	0.00214	0.0418	$0.0164^{+0.0062}_{-0.0035}$
200	0.0004799	0.0113	$0.00671^{+0.00122}_{-0.00061}$
250	0.000122	0.0132	$0.00556^{+0.00114}_{-0.00077}$
300	0.0000314	0.00581	$0.00538^{+0.00104}_{-0.00076}$

Table II: NLO cross-sections and cross-section limits for stops, assuming a charge survival probability of 38%.

Mass [GeV]	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit $\pm 1\sigma$ [pb]
100	15.6	0.562	$0.218^{+0.078}_{-0.062}$
150	1.58	0.113	$0.0490^{+0.0190}_{-0.0111}$
200	0.266	0.0529	$0.0234^{+0.0106}_{-0.0037}$
250	0.0560	0.0269	$0.0201^{+0.0037}_{-0.0090}$
300	0.0130	0.0794	$0.0529^{+0.0140}_{-0.0128}$

Table III: NLO cross-sections and cross-section limits for gaugino-like charginos.

Mass [GeV]	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit $\pm 1\sigma$ [pb]
100	1.33	0.387	$0.153^{+0.068}_{-0.043}$
150	0.235	0.0435	$0.0167^{+0.0054}_{-0.0033}$
200	0.0566	0.0195	$0.00945^{+0.00368}_{-0.00057}$
250	0.0153	0.0136	$0.00988^{+0.00402}_{-0.00127}$
300	0.00417	0.0741	$0.0185^{+0.0046}_{-0.0027}$

Table IV: NLO cross-sections and cross-section limits for higgsino-like charginos.

Mass [GeV]	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit $\pm 1\sigma$ [pb]
100	0.381	0.106	$0.110^{+0.050}_{-0.032}$
150	0.0736	0.0417	$0.0165^{+0.0053}_{-0.0038}$
200	0.0186	0.0128	$0.00852^{+0.00169}_{-0.00112}$
250	0.00525	0.00897	$0.00716^{+0.00267}_{-0.00100}$
300	0.00154	0.0174	$0.0119^{+0.0033}_{-0.0005}$

8. Summary

In summary, we have performed a search for charged, massive long-lived particles using 5.2 fb^{-1} of integrated luminosity with the D0 detector. We find no evidence of signal and set 95% C.L. cross-section upper limits which vary from 0.04 pb to 0.006 pb for pair-produced stau leptons with masses in the range between 100 and 300 GeV. At 95% C.L. we exclude pair-produced long-lived stop quarks with mass below 265 GeV, gaugino-like charginos below 251 GeV, and higgsino-like charginos below 230 GeV. These are presently the most restrictive limits for chargino CMLLPs, with about a factor of five improvement over the previous D0 cross section limits [13].

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